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FRACTURE TOUGHNESS OF WIDE 2014-T6 ALUMINUM SHEET AT -320° F

by Thomas W. Orange

Lewis Research Center
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SUMMARY

An experimental program was conducted to investigate the effect of test specimen size on the plane-stress fracture-toughness parameter K_c and to provide a broad base of data for comparing the effectiveness of several methods of fracture analysis. Fracture specimens 3, 6, and 12 inches (7.5, 15, and 30 cm) wide of 2014-T6 aluminum alloy 0.060 inch (1.5 mm) thick having initial notches from 1/8 inch (3.2 mm) to one-third the specimen width were tested at -320° F (77° K). Critical crack length was measured with the NASA continuity gage. Conventional smooth and notched tensile properties were measured at 70°, -320°, and -423° F (293°, 77°, and 20° K). The fracture data obtained were used to compare the fracture analyses by G. R. Irwin, R. G. Forman, and P. Kuhn. Curves are presented showing typical subcritical crack growth during loading to failure for several specimen geometries.

For the transverse direction, a 3-inch-wide (7.5 cm) specimen was adequate to determine K_c; for the tougher longitudinal direction, a wider specimen was required. For the 3-inch-wide specimens, maintaining the net fracture stress below 80 percent of the yield stress (as recommended by the ASTM Fracture Committee) did not ensure a valid test. Essentially constant values of K_c were obtained when net fracture stresses were below about 75 percent of yield. Fracture toughness values calculated by Forman's method did not differ markedly from those calculated by the Griffith-Irwin method. Applicability of Kuhn's method is somewhat uncertain because of the variability shown by the crack sensitivity coefficient.

INTRODUCTION

Space vehicle propellant tanks are often made of high-strength materials in relatively thin gages, stressed nearly to the point of yielding, and subjected to cryogenic temperatures. The possibility of brittle fracture under such conditions requires that a suitable fracture analysis be performed. An analysis based on fracture mechanics principles requires knowledge of the material fracture toughness K_c, which must be determined experimentally. Values of K_c applicable to material of sheet thickness can be determined from tensile tests of notched or precracked sheet specimens. Such a test, however, has several aspects which require careful consideration.

The Griffith-Irwin theory commonly used to calculate K_c is based on a linear elastic analysis with a semiempirical correction for the effect of plastic flow at the crack tip. As the average stress in the uncracked net section of a test specimen (or structure) approaches the material yield stress, the validity of this approach becomes more uncertain. In order to obtain a valid measurement of K_c, the dimensions of the test specimen (particularly the specimen width and crack length) must be large enough to ensure that failure will occur prior to yielding.

The effects of inadequate specimen width and crack length are to reduce the apparent K_c value calculated, which may lead to overly conservative design. Materials of higher toughness, which are currently being developed, generally require wider specimens for valid K_c determination. For these reasons, the use of a test specimen of generous size is preferred. However, the economics of testing (particularly at cryogenic temperatures) dictates the use of a specimen not larger than necessary to obtain a valid test.

At present, there is no absolute criterion for determining the validity of a single K_c test. The ASTM Committee on Fracture Testing of High Strength Sheet Materials initially suggested (ref. 1) that a fracture test be considered valid as long as the net section fracture stress σ_n was less than the conventional yield stress σ_{ys}; this suggested criterion was later revised (ref. 2) to $\sigma_n < 0.8\,\sigma_{ys}$. The revised recommendation was based on a limited number of tests and should be subject to further study.

Determination of K_c requires the determination of a "critical crack length," and this requirement presents a twofold problem: Crack growth must be measured as the specimen is loaded to failure and some measured crack length must be taken as "critical." Reference 3 suggests several methods of crack growth measurement, namely, cinematography, electrical potential measurement, displacement gages, and continuity gages. The first three methods present formidable problems when applied at cryogenic temperatures. Prior experience (ref. 4) with the continuity gage developed at the Lewis Research Center prompted the choice of this method for the present study.

During fracture tests of practical engineering materials, there often is no abrupt, clearly delineated transition from slow to rapid crack propagation. Thus, unambiguously defining any measured crack length as critical is often difficult. A discussion of this problem is beyond the scope of the present report. As described in APPARATUS AND PROCEDURE, however, the continuity gage as used in this investigation imposes a criterion based upon crack velocity; that is, the crack length taken as critical is the length at which the crack propagation velocity has increased to a given level.

Linear elastic fracture mechanics theories are applicable only when net stresses are less than some fraction of the yield strength. However, cases of small cracks in large structures stressed nearly to the yield strength are not without interest to the designer. Attempts have been made to extend the range of applicability of fracture analysis to states of higher stress. One such analysis by Kuhn (ref. 5) was suggested as being applicable for net stresses below or equal to the yield strength. This method is based on ultimate tensile strength, an elastic stress concentration factor, and an experimentally determined coefficient of crack sensitivity. An analysis by Forman (ref. 6) takes into account the effect of the presence of the yield zone at the crack tip on the elastic stress distribution in the specimen using Dugdale's model (ref. 7) for the yield zone. Although it was not specifically so formulated, this analysis might be more accurate than the Griffith-Irwin method at high stress levels. Data obtained in the present report were used to examine both these methods and the results were compared with those obtained using the Griffith-Irwin analysis.

The investigation was made (1) to obtain basic data on the fracture behavior of small notches in wide specimens at high net-to-yield stress ratios, (2) to determine experimentally K_c and the smallest specimen adequate for its valid measurement, using 0.060-inch-thick (1.5 mm) 2014-T6 aluminum sheet specimens at -320° F (77° K), and (3) to determine the applicability of some alternate methods of fracture analysis.

The results of an NASA-Lewis investigation similar in scope to this investigation but using 5Al-2.5Sn extra-low-interstitial (ELI) titanium alloy 0.020 inch (0.5 mm) thick at -423° F (20° K) are presented in reference 8.

SYMBOLS

a one-half critical crack length

a_g one-half critical crack length indicated by continuity gage

a_o one-half original notch length

C_m crack sensitivity coefficient (ref. 5)

E elastic (Young's) modulus

K_c fracture toughness (based on critical crack length)

K_{cn} nominal fracture toughness (based on original notch length)

K_u stress concentration factor (ref. 5)

K_W	configuration factor (ref. 5)
L	effective specimen length
t	specimen thickness
W	specimen width at test section
γ	correction factor (ref. 6)
σ	gross fracture stress, max. load/tW
σ_{ns}	notched tensile strength, max. load/t(W - $2a_o$)
σ_n	net fracture stress, max. load/t(W - 2a)
σ_u	ultimate tensile strength (unnotched)
σ_{ys}	yield strength (0.2 percent offset)

MATERIAL AND TEST SPECIMENS

The 2014-T6 aluminum alloy was obtained in the form of unclad sheets 72 by 72 by 0.060 inches (183 by 183 by 0.15 cm). Chemical analysis by an independent testing laboratory gave the following composition in percent by weight: copper, 4.45; silicon, 0.92; manganese, 0.69; magnesium, 0.57; iron, 0.60; zinc, 0.05; chromium, 0.04; titanium, 0.02; nitrogen, 0.0012; hydrogen, 0.0005; oxygen, less than 0.0005; aluminum, balance.

Specimens for conventional smooth and notch-tensile tests were shaped as shown in figure 1. For these notched specimens, the configuration and the method of notch preparation were as recommended by the ASTM Fracture Committee in reference 1. Wider specimens for fracture toughness tests are shown in figure 2. The central notches were rough-machined to shape, and then the notch roots were finished by a shaper-type process to radii less than 0.0005 inch (0.013 mm). This radius was considered sharp enough to simulate a natural crack on the basis of the results of reference 9, figure 7 of which shows that the notch tensile strength of 2014-T6 aluminum tensile specimens no longer decreases significantly as the notch root radius is reduced below 0.001 inch (0.025 mm).

APPARATUS AND PROCEDURE

Specimens up to 3 inches (7.5 cm) wide were tested in a 20 000-pound- (89 000 N) capacity hydraulic tensile testing machine. Strain in the smooth tensile specimens was measured by using a clamp-on differential-transformer extensometer of 2-inch (5 cm) gage length and an autographic stress-strain recorder. The extensometer was previously calibrated at all test temperatures with a micrometer-driven calibration device. Cryogenic test temperatures were established by immersing the specimen in liquid nitrogen or liquid hydrogen. A vacuum-jacketed cryostat was used to minimize boiloff. Correct cryogenic temperature was assured by maintaining the liquid level several inches above the upper specimen grip. Liquid-level sensing was accomplished by means of carbon resistors.

The larger specimens were tested in a 400 000-pound- (1.8 MN) capacity screw-powered tensile machine. The cryostat for these tests used expanded mineral powder insulation. A whiffletree system of links, shown in figure 3, was used to assure uniform distribution of load. For specimens having initial notches 2 inches (5 cm) or longer, guide plates were used (fig. 4) to prevent local buckling of the crack lips resulting from transverse compressive strains. Reference 10 indicates that notch buckling does not occur when applied net stresses are less than $\pi^2Et^2/12a^2$. In the present study, all specimens tested without antibuckling guides failed at net stresses less than that given by the preceeding expression.

The NASA continuity gage, its method of application, and the interpretation and correction of test readout are described in detail in reference 4 but will be reviewed briefly here. The foil gage (fig. 5) consists of 20 filaments physically and electrically in parallel; it is bonded to the specimen at the crack tip with its filaments perpendicular to the expected direction of crack propagation. As the crack grows, successive filaments fracture to produce a stepwise change in electrical resistance, which is recorded on a direct-writing oscillograph along with a load signal from an appropriate transducer. In the present investigation, the critical crack length was taken to be the point at which successive steps on the oscillograph trace could no longer be visually distinguished. This determination obviously is influenced by filament spacing, galvanometer response, chart speed, and the overall resolution of the oscillograph. With the instrument settings that were used, the point taken as critical corresponded to a crack propagation velocity of about 0.5 to 1.0 inch (1.3 to 2.5 cm) per second.

The continuity gage filaments fracture at a finite strain level; hence, when a significant plastic zone exists at the crack tip, the continuity gage may tend to overestimate the actual crack length. The analytical correction equation given in reference 4 (eq. (1)) was used to correct all crack-length data.

Specimens 2 by 8 inches (5 by 20 cm) overall were tested at 70°, -320°, and -423° F (293°, 77°, and 20° K) to determine smooth and notched tensile strength. Fracture toughness specimens 3 by 12 inches (7.5 by 30 cm) and larger were tested at -320° F (77° K) only. Specimens tested in the hydraulic tensile machine were loaded at an elastic strain rate less than about 0.005 inch per inch per minute (0.00008 cm/cm/sec); specimens in the screw-powered tensile machine were tested with a crosshead speed of about 0.05 inch per minute (0.002 cm/sec).

RESULTS AND DISCUSSION

Averages of the data obtained from the smooth and notched tensile specimens are listed in table I and plotted in figure 6. These values represent the averages of five or more specimens for each test condition. Average values of experimental results for the fracture specimens, along with fracture parameters calculated, are listed in table II. Individual data for the fracture specimens are listed in table III.

Conventional Tensile and Notch-Screening Tests

In figure 6, the ultimate and yield strengths and the elastic moduli for this alloy increase with decreasing test temperature. The notch strength for the notched specimens of figure 1 was nearly constant. A slight degree of anisotropy, probably due to rolling of the sheet during fabrication, can also be seen.

Effect of Initial Notch Length, Specimen Width, and Stress Ratio on Apparent Fracture Toughness

Average apparent fracture toughness values are plotted against initial notch lengths in figure 7. As notch lengths are reduced below a certain value, a marked decrease in apparent fracture toughness occurs, signifying that the conditions of a valid test are no longer being met. Comparing the averages for the longitudinal and transverse directions shows that material of higher toughness (longitudinal) do, indeed, require longer notches and wider specimens for obtaining a valid K_c measurement.

In the present report, the true value of K_c (as distinguished from apparent values) is taken as that value which remains essentially constant with increases in specimen width and/or notch length. For the subject alloy at -320° F (77° K), this value was 64.3 ksi$\sqrt{\text{in.}}$ (70.7 MN$\sqrt{\text{m}}/\text{m}^2$) for the longitudinal direction and 52.8 ksi$\sqrt{\text{in.}}$ (58.0 MN$\sqrt{\text{m}}/\text{m}^2$) for the transverse direction.

Examination of the averages for the 3-inch-wide (7.5 cm) specimens shows that a sufficiently long notch in a transverse specimen gives the same K_c value as was obtained with wider specimens. For longitudinal specimens of the same width, however, even the longest notch tested resulted in apparent K_c values considerably less than those obtained with wider specimens.

In figure 8, average apparent fracture toughness is plotted against the ratio of net fracture stress (based on critical crack length) to yield strength. Again, the decrease in apparent K_c with shorter notch lengths (higher stress ratios) may be seen. Unfortunately, the stress ratio at which this decrease begins to occur does not appear to be constant. Note that, with the 3-inch-wide (7.5 cm) specimens, low apparent K_c values were obtained at stress ratios less than 0.8, the criterion recommended in reference 2. Hence, stress ratio should not be used as the sole criterion for deciding the validity of a K_c test. In general, it would appear that the narrower the specimen, the lower the stress ratio above which the decrease in apparent K_c occurs.

Consideration of the concept of specimen measurement capacity assists in understanding the behavior of these specimens. Measurement capacity is the largest value of K_c that may be validly measured when a specimen of given dimensions is used and is discussed in reference 3 (pp. 18-20). There, it was assumed that $\sigma_n < 0.8\,\sigma_{ys}$ is a sufficient condition for a valid test. On this basis and with the use of Irwin's expression for K_c, measurement capacity was shown to be maximum when the critical crack length is 30 to 40 percent of the specimen width, and then is approximately $0.45\,\sigma_{ys}\sqrt{W}$. For a 3-inch-wide (7.5 cm) specimen of the alloy tested in the present study, this value is about 59 ksi$\sqrt{\text{in.}}$ (65 MN$\sqrt{\text{m}}/\text{m}^2$), which is greater than transverse values but less than longitudinal values obtained with wider specimens. For comparison, a 6-inch-wide (15 cm) specimen of the same alloy should have a capacity of about 83 ksi$\sqrt{\text{in.}}$ (91 MN$\sqrt{\text{m}}/\text{m}^2$). Alternatively, the previous expression can be manipulated to state that the width of a specimen should be at least $5(K_c/\sigma_{ys})^2$ with the critical crack length 30 to 40 percent of the width.

It should be noted that the preceeding analysis was based on the criterion that $\sigma_n < 0.8\,\sigma_{ys}$. Figure 8 suggests that the fracture process is too complex for its limit of applicability to be adequately defined by the simple parameter σ_n/σ_{ys}. As discussed in reference 11 (pp. 20-24) it is more reasonable to require that the plastic zone size be small with respect to the crack length; in effect, this might require that the crack length be greater than some multiple of the Irwin plastic zone size $(1/2\pi)(K_c/\sigma_{ys})^2$. The determination of a minimum value for such a multiple requires the generation or compilation of applicable fracture data for a wide variety of materials. For the present, the analysis of reference 3 is the only method known to the author for estimating minimum dimensions for K_c test specimens.

Strength of Wide Fracture Specimens

In figure 9, the average values of gross fracture stress are plotted as a function of critical crack length at -320° F (77° K). Using the true values of K_c determined in figures 7 or 8 allows predicting fracture stresses by using two versions of the Griffith-Irwin expression:

$$\sigma = K_c (\pi a)^{-1/2} \tag{1}$$

$$\sigma = K_c \left[W \tan \left(\frac{\pi a}{W} + \frac{K_c^2}{2W\sigma_{ys}^2} \right) \right]^{-1/2} \tag{2}$$

The equation for the fracture stress in an infinitely wide flawed sheet with no correction for the plastic zone (eq. (1); dashed line, fig. 9) predicts much too high a fracture stress at short crack lengths to be of more than academic interest. With corrections for plastic zone size and finite width (eq. (2); solid line, fig. 9), a good fit to the data is obtained for longer crack lengths. However, for shorter crack lengths, as net stresses approach yield, fracture occurs at gross stress levels less than predicted. This difficulty is apparently inherent when the Griffith-Irwin expression in its present form is applied to engineering materials stressed near yield.

Kuhn's Analysis

The method referred to as notch strength analysis by Kuhn (ref. 5) differs from the usual fracture analyses in that it is based primarily on ultimate tensile strength and an elastic stress concentration factor and neglects subcritical crack growth. According to Kuhn, gross fracture stress can be predicted by the equation

$$\sigma = \left(1 - \frac{2a_o}{W}\right) \frac{\sigma_u}{K_u} \tag{3}$$

where

$$K_u = 1 + C_m K_w (a_o)^{1/2}$$

and

$$K_W^2 = \frac{1 - \frac{2a_o}{W}}{1 + \frac{2a_o}{W}}$$

Here C_m is an experimentally determined measure of crack sensitivity which varies from zero for a perfectly ductile material to 30 inches$^{-1/2}$ (19 cm $^{-1/2}$) or more for very brittle materials and is determined from a test on a cracked specimen.

From the average values of the data obtained in the present study (table II), values of the coefficient C_m were calculated. These values of C_m are included in table II and plotted in figure 10. It is readily apparent from figure 10 that a constant value of C_m was not obtained but, rather, values ranging from 1.15 to 2.51 inches$^{-1/2}$ (0.72 to 1.57 cm$^{-1/2}$). It also appears that C_m is independent of specimen width but increases approximately as the logarithm of the initial notch length.

The variability of C_m for this alloy leaves some uncertainty as to what value should be used to predict fracture stress. The effect of the C_m variability seen for 12-inch-wide (30 cm) specimens is shown in figure 11(a), which was constructed as follows: The smallest value of C_m calculated from tests of these specimens was used in equation (3) to predict gross fracture stress as a function of original notch length; this prediction gave the upper curve. When the largest calculated value of C_m was used in equation (3), the lower curve resulted. Averages of the test data were plotted as points. The data points for the shortest and longest notch lengths fall on the upper and lower curves, respectively, because the C_m values calculated from them were used to generate the curves. Figure 11(b) was constructed by repeating this procedure for the transverse direction.

For 2014-T6 aluminum alloy, the greater the net stress (shorter crack lengths) and the higher the toughness (longitudinal direction), the less the effect of C_m variability on predicted fracture stress. Thus, it appears that Kuhn's analysis may be useful when linear elastic fracture mechanics should not be used; that is, when net fracture stresses are very near or above yield. For the subject alloy, however, when net stresses are below about 75 percent of yield, the Griffith-Irwin method predicts fracture stress with much greater accuracy, as can be seen by comparing figure 11 with figure 9.

Forman's Method

The analysis by Forman (ref. 6) is intended to derive a more accurate solution for the strain energy release rate by using a model which does not assume that the elastic stress distribution is unaltered by the presence of the yield zone at the crack tip. Fracture toughness is given by

$$K_c = \sigma\gamma\sqrt{\pi a} \tag{4}$$

where γ is a complicated function of specimen geometry, critical crack length, gross fracture stress, and material yield strength. Irwin's expression (eq. (2)) is explicit in terms of fracture stress but implicit in terms of fracture toughness; whereas, Forman's expression (eq. (4)) is just the opposite. For this reason, no attempt was made to predict fracture stress by Forman's method. Rather, fracture toughness values were calculated (for the longitudinal direction only) and compared with those obtained by using the Griffith-Irwin equation.

Because the strain energy function was derived from an expression for the axial rigidity of a perforated plate, the plate length appears in the expression for the strain energy release rate. To simplify the expression, Forman assumes that the length of the plate is much greater than its width. The overall length of the specimens tested in the present study was only four times the test section width; also, the effect of this approximation on a practical problem was of interest. Therefore, fracture toughness was calculated by assuming the specimen infinitely long ($W/L \approx 0$ in table II and fig. 12) and also by assuming an effective length equal to the distance between loading-pin centerlines ($W/L \neq 0$).

At this point, it should be noted that perhaps the effect of testing machine stiffness could be incorporated by means of a suitable expression for the effective specimen length.

Fracture toughness values calculated in three ways (Irwin's method and the two variations of Forman's method) are plotted against critical crack length in figure 12. Values calculated by Forman's method are higher (all cases but one) but by only about 5 ksi$\sqrt{\text{in.}}$ (5.5 MN$\sqrt{\text{m}}$/m^2) or less. Also, the effect of specimen length increases with crack length. However, the overall difference between methods is slight, at least for the material studied here.

Subcritical Flaw Growth

Figures 13 and 14 are considered to be typical examples of subcritical crack growth during single-cycle loading to failure. At present there are no known theories to permit a rational analysis of these data, but they are presented herein as information of current interest and for possible future use. These figures were constructed as follows: Continuity gage and load transducer signals were obtained from the oscillograph trace at selected intervals of crack growth. Values of gross stress and indicated crack length were calculated, and the analytical crack-length correction mentioned previously was applied. Growth data for three specimens (all but one case) having the same initial geometry were plotted; then a smooth curve was drawn to give a good visual average. Figure 13 shows typical growth from a 1-inch- (2.5 cm) long notch in specimens of three widths; figure 14 shows typical growth (normalized) for notches of six lengths in 12-inch- (30 cm) wide specimens.

CONCLUSIONS

From the results of this investigation of the fracture toughness of 2014-T6 aluminum sheet at -320° F (77° K), the following conclusions were made:

1. Plane-stress fracture toughness of this alloy at -320° F (77° K) was determined to be 64.3 ksi$\sqrt{\text{in.}}$ (70.7 MN$\sqrt{\text{m}}$/m^2) in the longitudinal direction and 52.8 ksi$\sqrt{\text{in.}}$ (58.0 MN$\sqrt{\text{m}}$/m^2) in the transverse direction. For the transverse direction a 3-inch- (7.5 cm) wide specimen was adequate to determine K_c; for the tougher longitudinal direction a wider specimen was necessary. Essentially constant values of K_c were obtained as long as the net fracture stress was less than about 75 percent of yield strength.
2. A fracture test should not be judged valid solely because the net fracture stress is less than 0.8 times yield strength. This maximum ratio of net fracture stress to yield strength recommended by the ASTM Fracture Committee is not low enough to guarantee a valid test for all materials.
3. Fracture toughness values calculated by Forman's method did not differ markedly from those calculated by the Griffith-Irwin method.
4. Applicability of Kuhn's method is uncertain because of the variability exhibited by the crack sensitivity coefficient C_m; however, this method may be useful for cases where net fracture stresses are near or above yield and linear elastic fracture mechanics should not be used.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 1, 1967,
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TABLE I. - SMOOTH AND NOTCHED TENSILE PROPERTIES

[Determined using specimens shown in fig. 1.]

(a) U. S. Customary units

Direction	Test temperature, T, ^{o}F	Ultimate tensile strength, σ_u, ksi	0. 2-Percent offset yield strength, σ_{ys}, ksi	Sharp-notch tensile strength, σ_{ns}, ksi	Elastic modulus, E, psi	Notch-to-yield strength ratio, σ_{ns}/σ_{ys}
Longitudinal	70	72. 3	65. 0	55. 24	10.4×10^{6}	0. 735
	-320	86. 65	75. 19	52. 62	11. 5	. 700
	-423	99. 67	80. 29	56. 22	11. 6	. 748
Transverse	70	74. 64	66. 78	54. 48	10.5×10^{6}	0. 717
	-320	88. 06	75. 95	57. 49	11. 9	. 757
	-423	101. 00	83. 90	50. 55	12. 4	. 666

(b) International System of units

Direction	Test temperature, T, ^{o}K	Ultimate tensile strength, σ_u, N/cm^2	0. 2-Percent offset yield strength, σ_{ys}, N/cm^2	Sharp-notch tensile strength, σ_{ns}, N/cm^2	Elastic modulus, E, gN/m^2	Notch-to-yield strength ratio, σ_{ns}/σ_{ys}
Longitudinal	293	49 850	44 820	38 090	71. 7	0. 735
	77	59 740	51 840	36 280	79. 3	. 700
	20	68 720	55 360	38 760	80. 0	. 748
Transverse	293	51 460	46 040	37 560	72. 4	0. 717
	77	60 720	52 360	39 640	82. 0	. 757
	20	69 640	57 850	34 850	85. 5	. 666

TABLE II. - AVERAGE FRACTURE DATA AND CALCULATED PARAMETERS

(a) U. S. Customary units; test temperature, -320° F

Direction	Nominal width, w, in.	Initial notch length, $2a_o$, in.	Critical crack length, 2a, in.	Gross fracture stress, σ, ksi	Notch tensile strength,[a] σ_{ns}, ksi	Net fracture stress,[b] σ_n, ksi	Net-to-yield stress ratio, σ_n/σ_{ys}	Crack sensitivity coefficient,[c] C_m, $(in.)^{-1/2}$	Nominal fracture toughness,[a] K_{cn}, ksi$\sqrt{in.}$	Fracture toughness, K_c, ksi$\sqrt{in.}$		
										(b)	(d)	(e)
Longitudinal	3	0.127	0.206	64.96	67.83	69.50	0.925	1.149	36.76	46.77	51.31	51.15
		.252	.390	55.90	61.05	64.27	.855	1.285	41.71	52.39	55.12	54.64
		.502	.809	44.55	53.52	61.06	.812	1.464	44.51	58.79	61.75	59.73
		1.001	1.287	32.53	48.87	57.06	.759	1.547	45.94	55.13	60.15	55.46
	6	0.127	0.213	66.07	67.52	68.51	0.911	1.148	37.77	48.90	53.82	53.77
		.251	.457	59.52	62.12	64.43	.857	1.162	45.23	61.31	65.15	64.95
		.500	.883	48.58	53.00	57.00	.758	1.380	49.48	65.56	71.13	69.93
		1.001	1.474	37.12	44.56	49.25	.654	1.580	50.56	62.76	69.18	67.45
		2.002	2.572	26.89	40.36	47.09	.627	1.622	52.43	62.37	68.63	63.77
	12	0.125	0.236	65.76	66.43	67.07	0.892	1.234	37.09	50.90	55.74	55.73
		.250	.421	58.66	59.92	60.81	.809	1.288	44.14	57.43	60.11	60.09
		.499	.842	49.64	51.80	53.38	.710	1.404	49.80	64.72	66.93	66.82
		.997	1.451	40.09	43.73	45.60	.607	1.511	54.43	65.95	67.41	67.08
		1.999	2.724	29.29	35.14	37.89	.504	1.735	54.51	64.81	67.40	66.30
		4.00	4.897	20.64	30.96	35.49	.472	1.800	55.77	64.90	68.00	64.46
Transverse	3	0.126	0.188	64.48	67.30	68.78	0.906	1.282	36.04	44.07	Not computed	
		.301	.423	49.99	55.56	58.20	.766	1.668	39.18	46.89		
		.498	.720	43.22	51.79	57.00	.751	1.659	42.58	52.55		
		1.001	1.361	30.23	45.35	55.32	.728	1.883	42.19	52.76		
	6	0.125	0.194	65.89	67.29	68.09	0.897	1.261	37.01	46.17		
		.251	.386	56.50	58.96	60.38	.795	1.453	41.78	51.95		
		2.00	2.556	22.74	34.12	39.64	.519	2.236	43.67	51.52		
	12	0.126	0.242	65.70	66.40	67.05	0.883	1.313	36.98	51.21		
		.254	.430	55.93	57.20	58.01	.764	1.546	41.40	53.93		
		.50	.763	43.79	46.10	46.76	.615	1.898	42.55	52.51		
		1.00	1.567	32.57	35.54	37.46	.493	2.272	43.06	54.15		
		2.00	2.415	26.37	31.65	33.07	.436	2.109	48.97	54.21		
		4.00	4.782	16.72	25.08	27.79	.366	2.511	44.72	50.18		

[a] Based on original notch length $2a_o$.
[b] Based on critical crack length 2a.
[c] Method of ref. 5.
[d] Method of ref. 6 with $W/L \neq 0$ (finite length, see p. 23).
[e] Method of ref. 6 with $W/L \approx 0$ (infinite length, see p. 23).

TABLE II. - Concluded. AVERAGE FRACTURE DATA AND CALCULATED PARAMETERS

(b) International System of units; test temperature, 77° K

Direction	Nominal width, w, cm	Initial notch length, $2a_o$, cm	Critical crack length, 2a, cm	Gross fracture stress, σ, N/cm^2	Notch tensile strength,[a] σ_{ns}, N/cm^2	Net fracture stress,[b] σ_n, N/cm^2	Net-to-yield stress ratio, σ_n/σ_{ys}	Crack sensitivity coefficient,[c] C_m, $cm^{-1/2}$	Nominal fracture toughness,[a] K_{cn}, $MN\sqrt{m}/m^2$	Fracture toughness, K_c, $MN\sqrt{m}/m^2$		
										(b)	(d)	(e)
Longitudinal	7.5	0.322	0.523	44 790	46 770	47 920	0.925	0.721	40.39	51.39	56.38	56.20
		.640	.991	38 540	42 090	44 310	.855	.806	45.83	57.57	60.57	60.04
		1.275	2.055	30 720	36 900	42 100	.812	.919	48.91	64.60	67.85	65.63
		2.543	3.269	22 430	33 700	39 340	.759	.971	50.48	60.58	66.09	60.94
	15	0.322	0.541	45 560	46 560	47 240	0.911	0.720	41.50	53.73	59.14	59.08
		.638	1.161	41 040	42 830	44 420	.857	.729	49.70	67.37	71.59	71.37
		1.270	2.243	33 500	36 540	39 300	.758	.866	54.37	72.04	78.16	76.84
		2.543	3.744	25 590	30 720	33 960	.654	.991	55.56	68.96	76.01	74.11
		5.085	6.533	18 540	27 830	32 470	.627	1.018	57.61	68.53	75.41	70.07
	30	0.318	0.599	45 340	45 800	46 240	0.892	0.774	40.75	55.93	61.25	61.24
		.635	1.069	40 450	41 310	41 930	.809	.808	48.50	63.10	66.05	66.03
		1.267	2.139	34 230	35 720	36 810	.710	.881	54.72	71.11	73.54	73.42
		2.532	3.686	27 640	30 150	31 440	.607	.948	59.81	72.47	74.07	73.71
		5.077	6.919	20 200	24 230	26 130	.504	1.089	59.90	71.21	74.06	72.85
		10.160	12.438	14 230	21 350	24 470	.472	1.129	61.28	71.31	74.72	70.83
Transverse	7.5	0.320	0.478	44 460	46 400	47 420	0.906	0.804	39.60	48.42	Not computed	
		.765	1.074	34 470	38 310	40 130	.766	1.047	43.05	51.52		
		1.265	1.829	29 800	35 710	39 300	.751	1.041	46.79	57.74		
		2.543	3.457	20 840	31 270	38 140	.728	1.181	46.36	57.97		
	15	0.318	0.493	45 430	46 400	46 950	0.897	0.791	40.67	50.73		
		.638	.980	38 960	40 650	41 630	.795	.912	45.91	57.08		
		5.080	6.492	15 680	23 530	27 330	.519	1.403	47.98	56.61		
	30	0.320	0.615	45 300	45 780	46 230	0.883	0.824	40.63	56.27		
		.645	1.092	38 560	39 440	40 000	.764	.970	45.49	59.26		
		1.270	1.938	30 190	31 790	32 240	.615	1.191	46.75	57.70		
		2.540	3.980	22 460	24 500	25 830	.493	1.426	47.31	59.50		
		5.080	6.134	18 180	21 820	22 800	.436	1.323	53.81	59.57		
		10.160	12.146	11 530	17 290	19 160	.366	1.576	49.14	55.14		

[a]Based on original notch length $2a_o$.
[b]Based on critical crack length 2a.
[c]Method of ref. 5.
[d]Method of ref. 6 with $W/L \neq 0$ (finite length, see p. 23).
[e]Method of ref. 6 with $W/L \approx 0$ (infinite length, see p. 23).

TABLE III. - EXPERIMENTAL FRACTURE DATA AND INDIVIDUALLY CALCULATED PARAMETERS

(a) U. S. Customary units; test temperature, -320° F

Direction	Specimen width, w, in.	Thickness, t, in.	Original notch length, $2a_o$, in.	Indicated critical crack length, $2a_g$, in.	Corrected critical crack length, 2a, in.	Gross fracture stress, σ, ksi	Net fracture stress, σ_n, ksi	Nominal fracture toughness, K_{cn}, ksi$\sqrt{in.}$	Fracture toughness, K_c, ksi$\sqrt{in.}$
Longitudinal	2.991	0.0612	0.128	(a)	(a)	65.68	(a)	37.56	(a)
	2.994	.0609	.127	0.368	0.210	65.50	70.42	37.24	48.16
	2.993	.0627	.124	.339	.200	64.36	68.99	35.80	45.72
	2.9905	.0612	.129	.350	.207	64.30	69.08	36.45	46.43
	2.992	.0612	.253	.587	.421	55.27	64.32	41.10	53.80
	2.991	.0623	.254	.506	.361	55.82	63.47	41.75	50.18
	2.996	.0621	.256	.540	.384	55.88	64.12	42.01	52.00
	2.9945	.0619	.247	.559	.392	56.63	65.17	41.99	53.59
	2.991	.0621	.498	1.014	.827	44.82	61.93	44.65	60.07
	2.991	.0624	.506	.978	.808	43.78	59.98	43.73	57.42
	2.994	.0612	.502	1.032	.840	44.87	62.36	44.91	60.78
	2.9915	.0613	.502	.928	.761	44.71	59.96	44.73	56.82
	2.994	.0606	.999	1.500	1.356	31.15	56.93	43.63	54.67
	2.995	.0616	1.003	1.379	1.234	33.22	56.50	47.14	54.70
	2.990	.0619	1.000	1.422	1.270	33.22	57.76	47.05	56.01
	5.9997	.0600	.1275	.375	.213	65.83	68.26	37.57	48.64
	5.9995	.0601	.127	.368	.205	66.42	68.77	38.03	48.41
	5.9998	.0600	.1275	.390	.221	65.97	68.49	37.70	49.65
	5.9995	.0612	.2515	.674	.450	59.50	64.33	45.25	60.80
	5.9995	.0616	.250	.680	.459	58.98	63.87	44.53	60.64

5.9995	0.0613	0.2515	0.700	0.461	60.09	65.09	45.90	62.48
5.9995	.0607	.501	1.156	.904	49.70	58.52	50.18	68.37
5.999	.0604	.4985	1.039	.837	47.47	55.16	51.86	61.80
5.9995	.0605	.501	1.333	1.038	49.72	60.14	50.22	73.86
5.996	.0598	.50	1.218	.864	48.24	56.38	48.26	64.22
5.995	.0602	.50	1.233	.890	47.38	51.69	47.17	63.74
5.995	.0603	.50	1.093	.766	48.96	56.14	49.18	61.37
5.999	.0607	1.0025	1.774	1.556	37.85	51.09	51.73	66.23
5.9995	.0603	1.002	1.767	1.537	38.81	52.18	53.26	67.77
5.9995	.0600	1.0025	1.693	1.495	37.08	49.40	50.54	63.16
5.9995	.0615	1.00	1.622	1.391	35.18	45.80	47.50	56.95
5.995	.0600	1.00	1.571	1.329	36.45	46.83	49.47	57.83
5.9955	.0612	1.00	1.840	1.534	37.34	50.17	50.86	64.63
5.9995	.0604	2.002	2.827	2.626	27.51	48.93	53.76	65.04
5.999	.0603	2.004	2.811	2.641	25.49	45.54	49.48	59.92
5.999	.0614	2.002	2.791	2.588	27.86	48.99	54.50	65.22
5.995	.0600	2.00	2.668	2.432	26.69	44.90	51.97	59.31
12.002	.0608	.125	.364	.208	65.78	66.94	37.11	47.84
12.002	.0604	.126	.446	.256	65.53	66.95	37.03	52.83
12.0015	.0600	.124	.429	.243	65.96	67.33	37.13	52.03
12.001	.0601	.250	.606	.407	59.34	61.43	44.85	57.29
12.001	.0603	.251	.609	.425	57.48	59.60	42.93	55.92
12.001	.0593	.250	.647	.437	59.15	61.39	44.65	59.07
12.001	.0600	.5005	1.155	.917	49.02	53.08	49.06	66.63
12.0015	.0604	.4985	1.080	.860	48.77	52.54	48.64	64.10

[a]No data because of test malfunction.

TABLE III. - Continued. EXPERIMENTAL FRACTURE DATA AND INDIVIDUALLY CALCULATED PARAMETERS

(a) Concluded. U. S. Customary units; test temperature, -320° F

Direction	Specimen width, w, in.	Thickness, t, in.	Original notch length, $2a_o$, in.	Indicated critical crack length, $2a_g$, in.	Corrected critical crack length, 2a, in.	Gross fracture stress, σ, ksi	Net fracture stress, σ_n, ksi	Nominal fracture toughness, K_{cn}, ksi$\sqrt{\text{in.}}$	Fracture toughness, K_c, ksi$\sqrt{\text{in.}}$
Longitudinal	12.0005	0.0599	0.499	0.988	0.748	51.13	54.52	51.71	63.42
	12.0005	.0605	.997	1.719	1.512	38.50	44.05	51.91	64.31
	12.0015	.0602	.998	1.598	1.373	41.38	46.73	56.52	66.58
	12.0005	.0590	.996	1.693	1.467	40.40	46.02	54.87	66.95
	12.0005	.0602	1.9985	2.912	2.698	30.18	38.93	56.61	66.64
	12.0007	.0595	2.000	2.961	2.757	29.27	38.00	54.77	65.22
	12.001	.0603	1.996	2.978	2.778	28.88	37.58	53.92	64.55
	11.996	.0611	2.00	2.852	2.661	28.83	37.04	53.72	62.81
	12.0015	.0606	4.00	5.198	5.026	19.37	35.25	52.17	64.37
	12.001	.0596	4.00	5.072	4.876	21.01	34.39	56.83	64.73
	12.0005	.0591	4.00	4.991	4.789	21.53	35.83	58.31	65.61
Transverse	3.002	0.0608	0.126	0.337	0.192	66.52	71.05	37.81	46.84
	3.002	.0583	.126	.257	.161	63.26	66.83	34.91	39.51
	3.002	.0584	.127	.342	.211	63.66	68.47	35.40	45.86
	3.002	.0587	.2995	.542	.424	50.40	58.69	39.49	47.44
	3.002	.0587	.3025	.547	.432	49.66	58.01	38.95	47.01
	3.002	.0584	.301	.525	.414	49.91	57.89	39.10	46.23
	3.002	.0613	.498	.768	.582	42.07	52.18	41.22	44.91
	3.004	.0605	.499	1.014	.847	43.37	60.37	42.81	58.22
	3.003	.0604	.496	.879	.732	44.21	58.46	43.71	54.51
	3.002	.0604	1.001	1.531	1.395	30.45	56.86	42.51	54.33

3.002	0.0611	1.005	1.417	1.297	30.37	53.46	42.50	50.97
3.006	.0613	.998	1.521	1.392	29.87	55.63	41.57	52.99
5.995	.0602	.125	.310	.181	65.95	67.99	37.05	44.58
5.996	.0614	.125	.339	.203	64.91	67.20	36.13	46.15
5.9955	.0603	.125	.351	.199	66.81	69.09	37.84	47.79
5.9975	.0611	.25	.519	.374	56.50	60.25	41.70	51.11
5.997	.0611	.25	.557	.399	56.77	60.81	42.00	53.21
5.998	.0611	.2525	.532	.385	56.22	60.07	41.63	51.53
5.997	.0610	2.00	2.672	2.551	22.85	39.77	43.90	51.72
5.996	.0610	2.00	2.649	2.536	22.26	38.57	42.69	50.04
5.996	.0610	2.00	2.708	2.582	23.10	40.57	44.42	52.80
11.997	.0601	.125	.428	.248	66.16	67.55	37.23	52.44
11.9985	.0598	.1263	.401	.235	65.78	67.09	37.09	50.60
11.9985	.0594	.1268	.406	.244	65.17	66.51	36.61	50.59
12.005	.0593	.254	.590	.443	53.94	56.01	39.42	52.12
12.000	.0596	.249	.623	.450	56.35	58.55	41.42	55.76
11.995	.0593	.258	.562	.398	57.50	59.47	43.36	53.91
11.997	.0579	.50	.819	.689	44.49	47.20	43.37	50.98
11.997	.0581	.50	1.070	.909	43.47	47.03	42.18	57.03
11.996	.0582	.50	.812	.691	43.40	46.05	42.10	49.53
11.996	.0607	1.00	1.705	1.561	33.30	38.29	44.08	55.39
11.997	.0606	1.00	1.769	1.607	29.09	33.59	38.01	48.47
11.997	.0604	1.00	1.694	1.532	35.33	40.50	47.08	58.59
11.997	.0605	2.00	2.328	2.218	25.14	30.85	46.48	49.11
11.997	.0601	2.00	2.773	2.611	27.60	35.28	51.35	59.30
11.998	.0600	4.00	4.763	4.651	16.97	27.72	45.45	50.05
11.999	.0596	4.00	5.040	4.923	16.72	28.36	44.76	51.21
11.999	.0597	4.00	4.900	4.799	15.85	26.40	42.33	47.58
11.999	.0610	4.00	4.877	4.756	17.32	28.70	46.42	51.89

TABLE III. - Continued. EXPERIMENTAL FRACTURE DATA AND INDIVIDUALLY CALCULATED PARAMETERS

(b) International System of units; test temperature, 77^{o} K

Direction	Specimen width, w, cm	Thickness, t, cm	Original notch length, $2a_o$, cm	Indicated crack length, $2a_g$, cm	Corrected critical crack length, 2a, cm	Gross fracture stress, σ, N/cm^2	Net fracture stress, σ_n, N/cm^2	Nominal fracture toughness, K_{cn}, $MN\sqrt{m}/m^2$	Fracture toughness, K_c, $MN\sqrt{m}/m^2$
Longitu-dinal	7.60	0.155	0.325	(a)	(a)	45 290	(a)	41.27	(a)
	7.60	.155	.323	0.935	0.533	45 160	48 550	40.92	52.92
	7.60	.159	.315	.861	.508	44 380	47 570	39.34	50.24
	7.60	.155	.328	.889	.526	44 330	47 630	40.05	51.02
	7.60	.155	.643	1.491	1.069	38 110	44 350	45.16	59.12
	7.60	.158	.645	1.285	.917	38 490	43 760	45.87	55.14
	7.61	.158	.650	1.372	.975	38 530	44 210	46.16	57.14
	7.61	.157	.627	1.420	.996	39 050	44 930	46.14	58.88
	7.60	.158	1.265	2.576	2.101	30 900	42 700	49.06	66.00
	7.60	.158	1.285	2.484	2.052	30 190	41 360	48.05	63.09
	7.60	.155	1.275	2.621	2.134	30 940	43 000	49.35	66.79
	7.60	.156	1.275	2.357	1.933	30 830	41 340	49.15	62.43
	7.60	.154	2.537	3.810	3.444	21 480	39 250	47.94	60.07
	7.61	.156	2.548	3.503	3.134	22 905	38 960	51.80	60.10
	7.59	.157	2.540	3.612	3.226	22 910	39 830	51.70	61.54
	15.24	.152	.324	.952	.541	45 390	47 070	41.28	53.45
	15.24	.153	.324	.935	.521	45 800	47 420	41.79	53.19
	15.24	.152	.324	.991	.561	45 490	47 220	41.42	54.56
	15.24	.155	.639	1.712	1.143	41 030	44 360	49.72	66.81
	15.24	.156	.635	1.727	1.166	40 670	44 040	48.93	66.63

	15.24	0.156	0.639	1.778	1.171	41 430	44 880	50.43	68.65
	15.24	.154	1.273	2.936	2.296	34 270	40 350	55.14	75.12
	15.24	.153	1.266	2.639	2.126	32 730	38 030	56.98	67.91
	15.24	.154	1.273	3.386	2.637	34 280	41 470	55.18	81.16
	15.23	.152	1.270	3.094	2.195	33 260	38 870	53.03	70.56
	15.23	.153	1.270	3.132	2.261	32 670	35 640	51.83	70.04
	15.23	.153	1.270	2.776	1.946	33 760	38 710	54.04	67.43
	15.24	.154	2.546	4.506	3.952	26 100	35 230	56.84	72.77
	15.24	.153	2.545	4.488	3.904	26 760	35 980	58.52	74.47
	15.24	.152	2.546	4.300	3.797	25 570	34 060	55.53	69.40
	15.24	.156	2.540	4.120	3.533	24 260	31 580	52.19	62.58
	15.23	.152	2.540	3.990	3.376	25 130	32 290	54.36	63.54
	15.23	.155	2.540	4.674	3.896	25 750	34 590	55.88	71.02
	15.24	.153	5.085	7.181	6.670	18 970	33 740	59.07	71.47
	15.24	.153	5.090	7.140	6.708	17 576	31 400	54.37	65.84
	15.24	.156	5.085	7.089	6.574	19 210	33 780	59.88	71.66
	15.23	.152	5.080	6.777	6.177	18 400	30 960	57.10	65.17
	30.48	.154	.318	.925	.528	45 360	46 160	40.78	52.57
	30.48	.153	.320	1.133	.650	45 180	46 160	40.69	58.05
	30.48	.152	.315	1.090	.617	45 480	46 420	40.80	57.17
	30.48	.153	.635	1.539	1.034	40 910	42 360	49.28	62.95
	30.48	.153	.638	1.547	1.080	39 630	41 000	47.17	61.44
	30.48	.151	.635	1.643	1.110	40 780	42 330	49.06	64.91
	30.48	.152	1.271	2.934	2.329	33 800	36 600	53.91	73.21
	30.48	.153	1.266	2.743	2.184	33 630	36 230	53.45	70.43

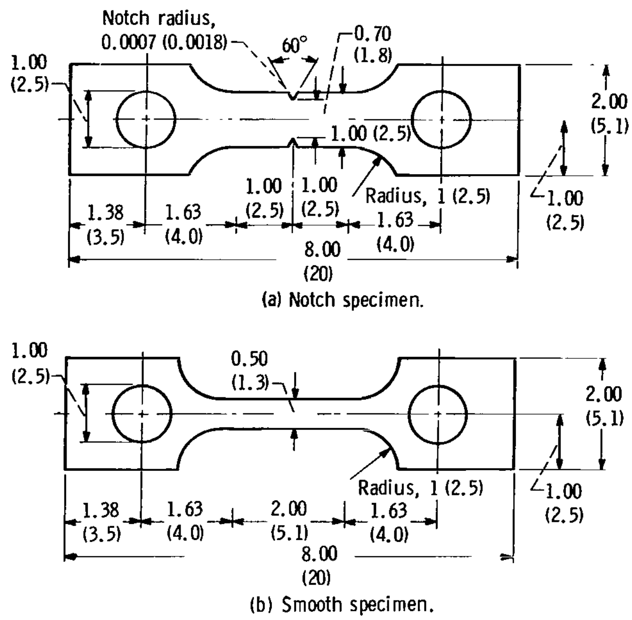
[a]No data because of test malfunction.

TABLE III. - Concluded. EXPERIMENTAL FRACTURE DATA AND INDIVIDUALLY CALCULATED PARAMETERS

(b) Concluded. International System of units; test temperature, 77° K

Direction	Specimen width, w, cm	Thickness, t, cm	Original notch length, $2a_o$, cm	Indicated crack length, $2a_g$, cm	Corrected critical crack length, 2a, cm	Gross fracture stress, σ, N/cm^2	Net fracture stress, σ_n, N/cm^2	Nominal fracture toughness, K_{cn}, $MN\sqrt{m}/m^2$	Fracture toughness, K_c, $MN\sqrt{m}/m^2$
Longitu- dinal	30.48	0.152	1.267	2.459	1.900	35 250	37 590	56.82	69.69
	30.48	.154	2.532	4.366	3.840	26 550	30 370	57.04	70.66
	30.48	.153	2.535	4.059	3.487	28 530	32 220	62.10	73.16
	30.48	.150	2.530	4.300	3.726	27 860	31 730	60.29	73.56
	30.48	.153	5.076	7.396	6.853	20 810	26 840	62.20	73.22
	30.48	.151	5.080	7.521	7.003	20 180	26 200	60.18	71.66
	30.48	.153	5.070	7.564	7.056	19 910	25 910	59.25	70.93
	30.47	.155	5.080	7.244	6.759	19 880	25 540	59.03	69.02
	30.48	.154	10.160	13.203	12.766	13 360	24 300	57.32	70.73
	30.48	.151	10.160	12.883	12.385	14 490	24 400	62.44	71.13
	30.48	.150	10.160	12.677	12.164	14 840	24 700	64.07	72.09
Trans- verse	7.62	0.154	0.320	0.856	0.488	45 870	48 990	41.55	51.47
	7.62	.148	.320	.653	.409	43 620	46 080	38.36	43.41
	7.62	.148	.323	.869	.536	43 890	47 210	38.90	50.39
	7.62	.149	.761	1.377	1.077	34 750	40 470	43.39	52.13
	7.62	.149	.768	1.389	1.097	34 240	40 000	42.80	51.65
	7.62	.148	.765	1.334	1.052	34 410	39 920	42.96	50.80
	7.62	.156	1.265	1.951	1.478	29 010	35 980	45.29	49.35
	7.63	.154	1.267	1.951	2.151	29 900	41 630	47.04	63.97
	7.63	.153	1.260	2.233	1.859	30 480	40 310	48.03	59.90
	7.62	.153	2.543	3.889	3.543	21 000	39 200	46.71	59.70

7.62	0.155	2.553	3.599	3.294	20 940	36 860	46.70	56.01
7.64	.156	2.535	3.863	3.536	20 600	38 360	45.68	58.23
15.23	.153	.318	.787	.460	45 470	46 880	40.71	48.98
15.23	.156	.318	.861	.516	44 760	46 330	39.70	50.71
15.23	.153	.318	.892	.505	46 070	47 640	41.58	52.51
15.23	.155	.635	1.318	.950	38 960	41 540	45.82	56.16
15.23	.155	.635	1.415	1.013	39 140	41 930	46.15	58.47
15.23	.155	.641	1.351	.978	38 760	41 420	45.74	56.62
15.23	.155	5.080	6.787	6.480	15 760	27 420	48.24	56.83
15.23	.155	5.080	6.728	6.441	15 350	26 590	46.91	54.98
15.23	.155	5.080	6.878	6.558	15 930	27 970	48.81	58.02
30.47	.153	.318	1.087	.630	45 620	46 580	40.91	57.62
30.48	.152	.321	1.019	.597	45 360	46 260	40.75	55.60
30.48	.151	.322	1.031	.620	44 930	45 860	40.23	55.59
30.49	.151	.645	1.499	1.125	37 190	38 620	43.31	57.27
30.48	.151	.632	1.582	1.143	38 850	40 370	45.51	61.27
30.47	.151	.655	1.427	1.011	39 650	41 000	47.64	59.24
30.47	.147	1.270	2.080	1.750	30 680	32 540	47.65	56.02
30.47	.148	1.270	2.718	2.309	29 970	32 430	46.35	62.66
30.47	.148	1.270	2.062	1.755	29 920	31 750	46.26	54.42
30.47	.154	2.540	4.331	3.965	22 960	26 400	48.44	60.86
30.47	.154	2.540	4.493	4.082	20 060	23 160	41.77	53.26
30.47	.153	2.540	4.303	3.891	24 360	27 920	51.73	64.38
30.47	.154	5.080	5.913	5.634	17 330	21 270	51.07	53.96
30.47	.153	5.080	7.043	6.632	19 030	24 330	56.42	65.16
30.47	.152	10.160	12.098	11.814	11 700	19 110	49.94	54.99
30.48	.151	10.160	12.802	12.504	11 530	19 550	49.18	56.27
30.48	.152	10.160	12.446	12.189	10 930	18 200	46.51	52.28
30.48	.155	10.160	12.388	12.080	11 940	19 790	51.01	57.02



(a) Notch specimen.

(b) Smooth specimen.

Figure 1. - Smooth and notched-sheet tensile specimens. (Dimensions in inches (or centimeters) except as noted.)

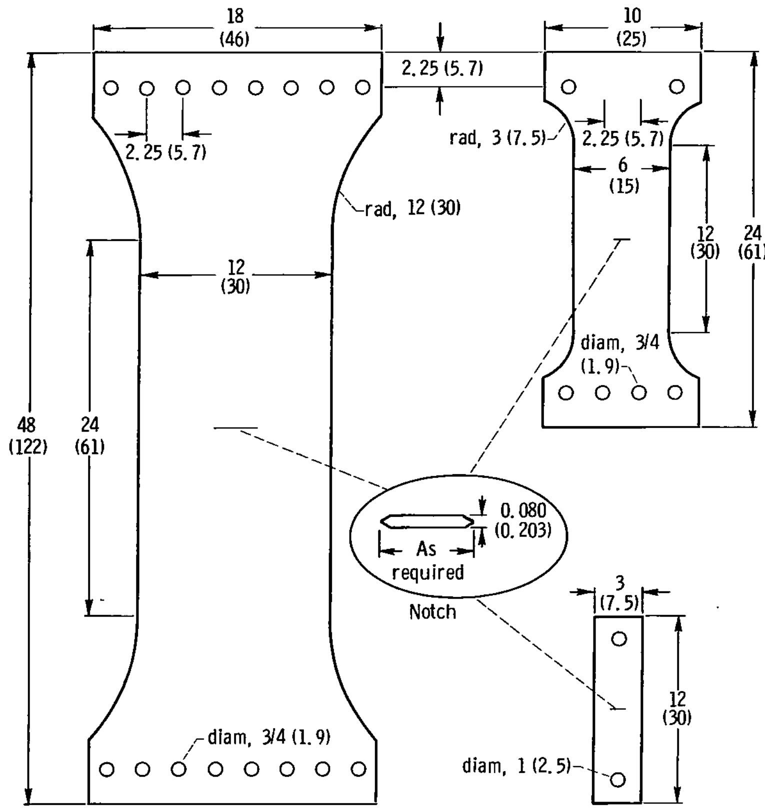


Figure 2. - Fracture toughness specimens. Notch root radii, 0.0005 inch maximum (0.0013 cm). (Dimensions in inches (or centimeters)).

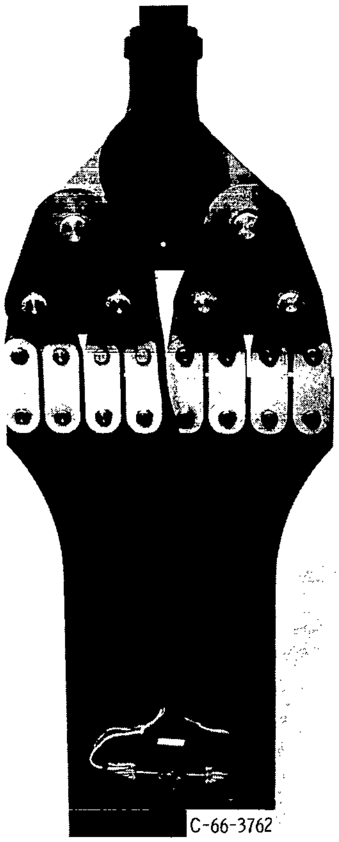


Figure 3. - Fracture specimen installed in whiffletree linkage for uniform loading.

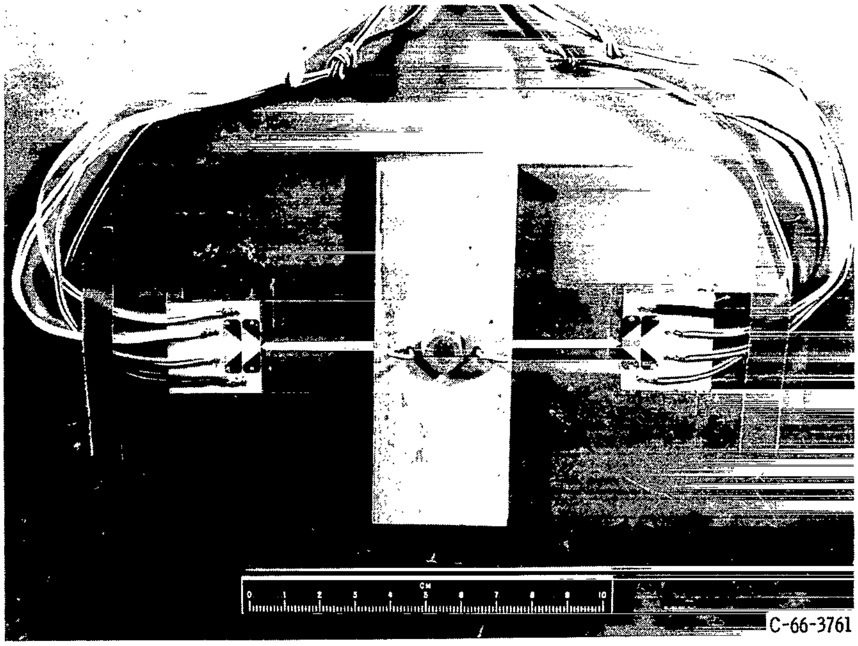


Figure 4. - Details of antibuckling plate and continuity gage installation.

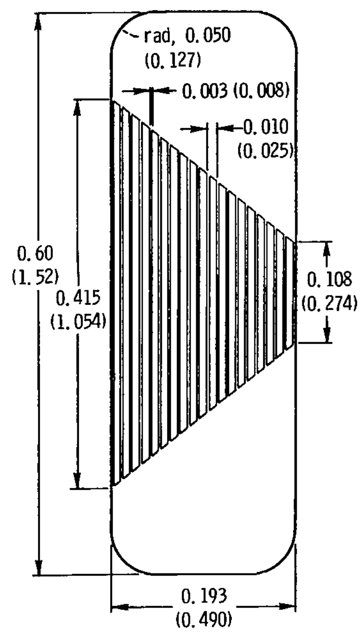


Figure 5. - NASA continuity gage. (Dimensions in inches or (centimeters)).

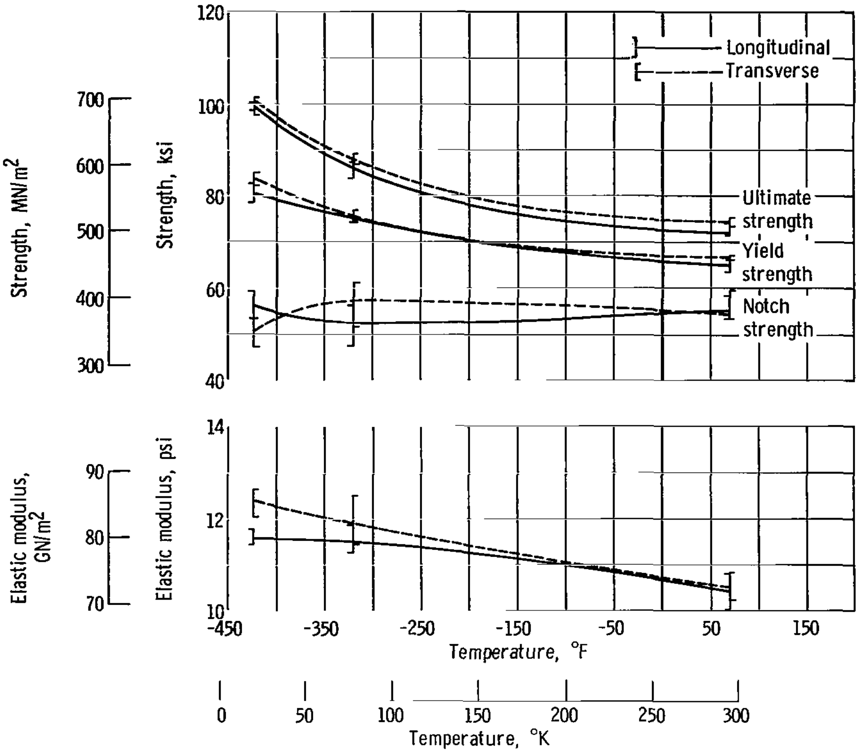


Figure 6. - Smooth and notched tensile properties (determined using specimens shown in fig. 1). Curves are drawn through average values; scatter is indicated by brackets.

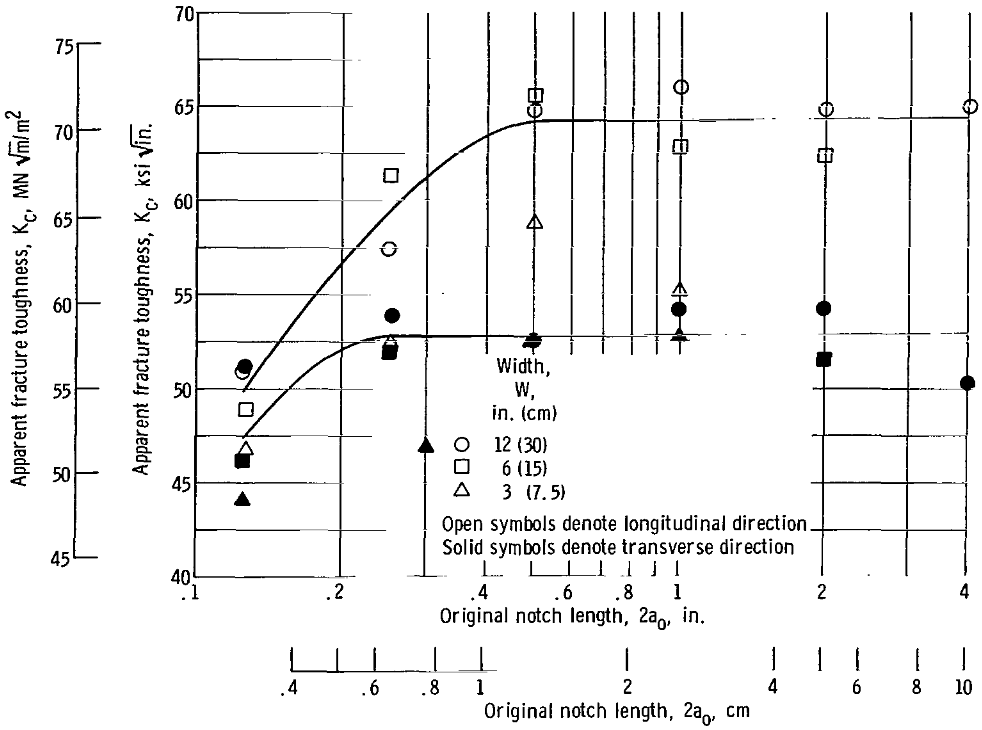


Figure 7. - Effect of original notch length on average apparent fracture toughness at -320° F (77° K).

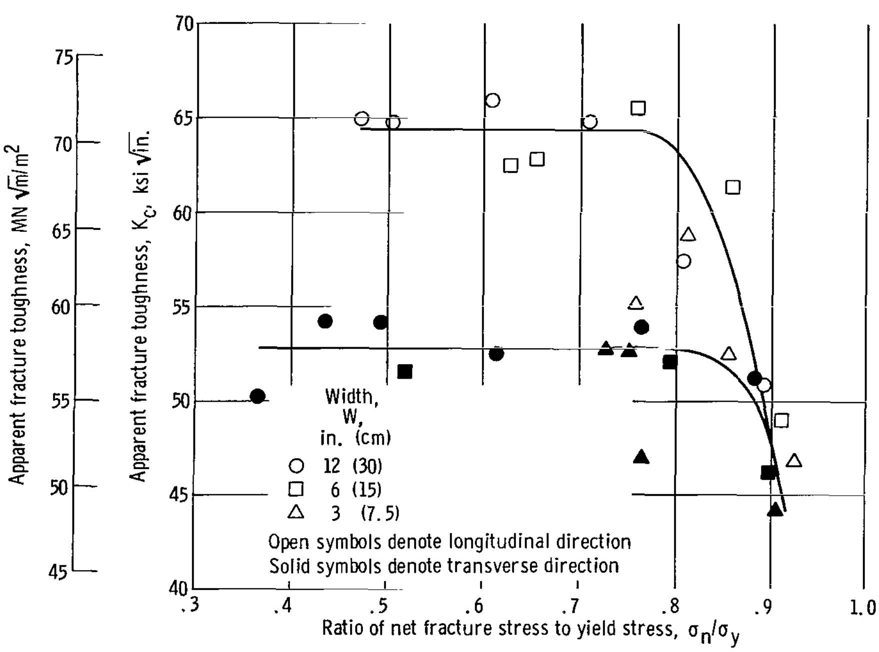
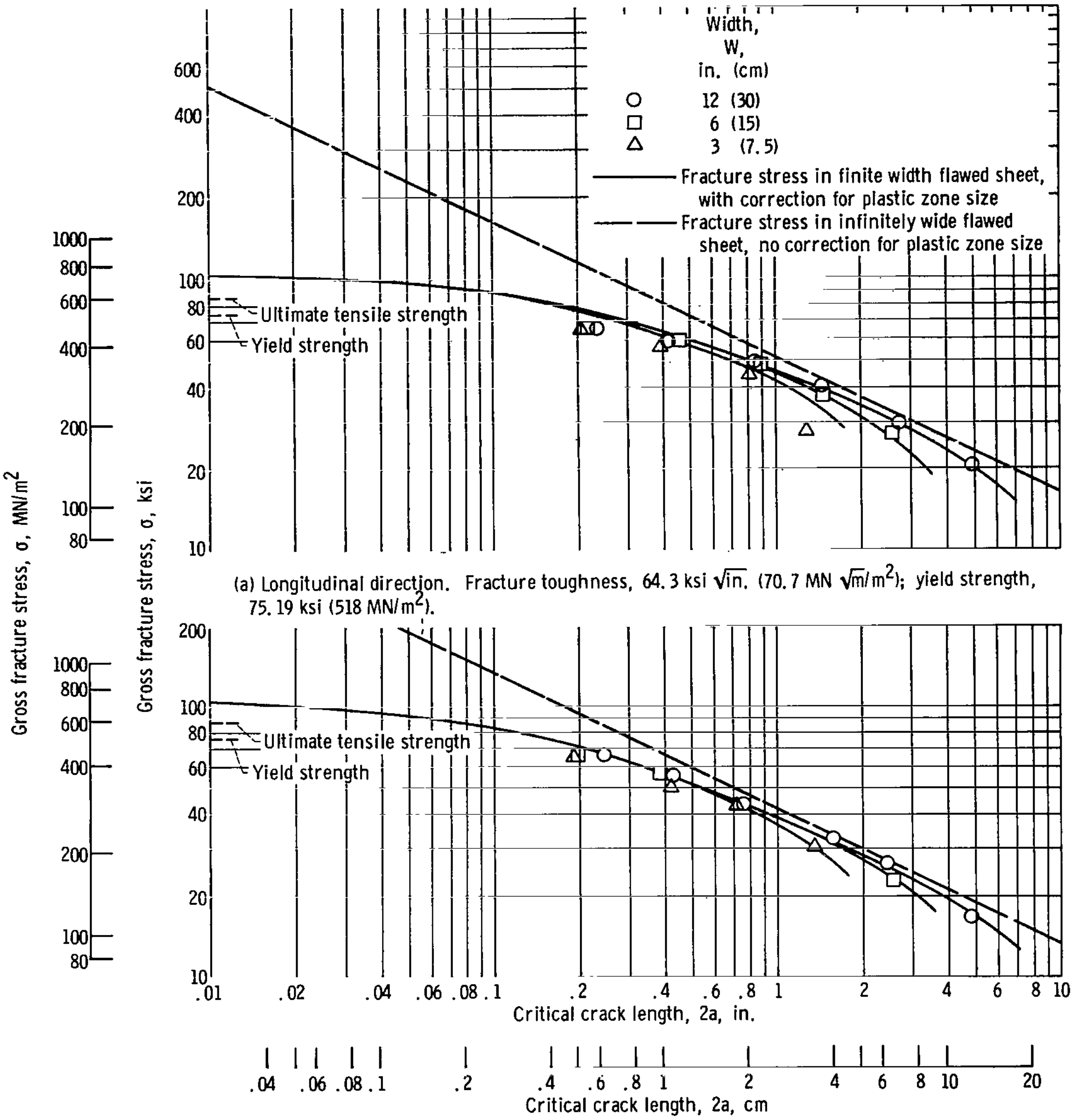


Figure 8. - Average apparent fracture toughness at -320° F (77° K) as function of stress ratio based on critical crack length.



(a) Longitudinal direction. Fracture toughness, 64.3 ksi $\sqrt{\text{in.}}$ (70.7 MN $\sqrt{\text{m}}/\text{m}^2$); yield strength, 75.19 ksi (518 MN/m²).

(b) Transverse direction. Fracture toughness, 52.8 ksi $\sqrt{\text{in.}}$ (58.0 MN $\sqrt{\text{m}}/\text{m}^2$); yield strength, 75.95 ksi (524 MN/m²).

Figure 9. - Average gross fracture stress as function of critical crack length at -320° F (77° K).

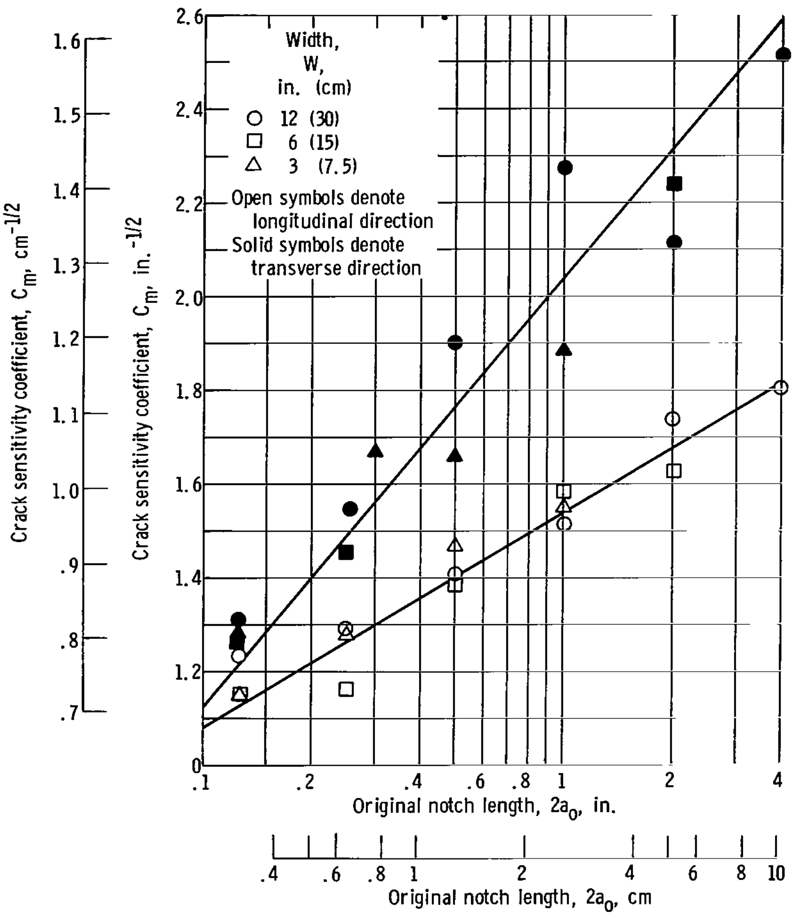
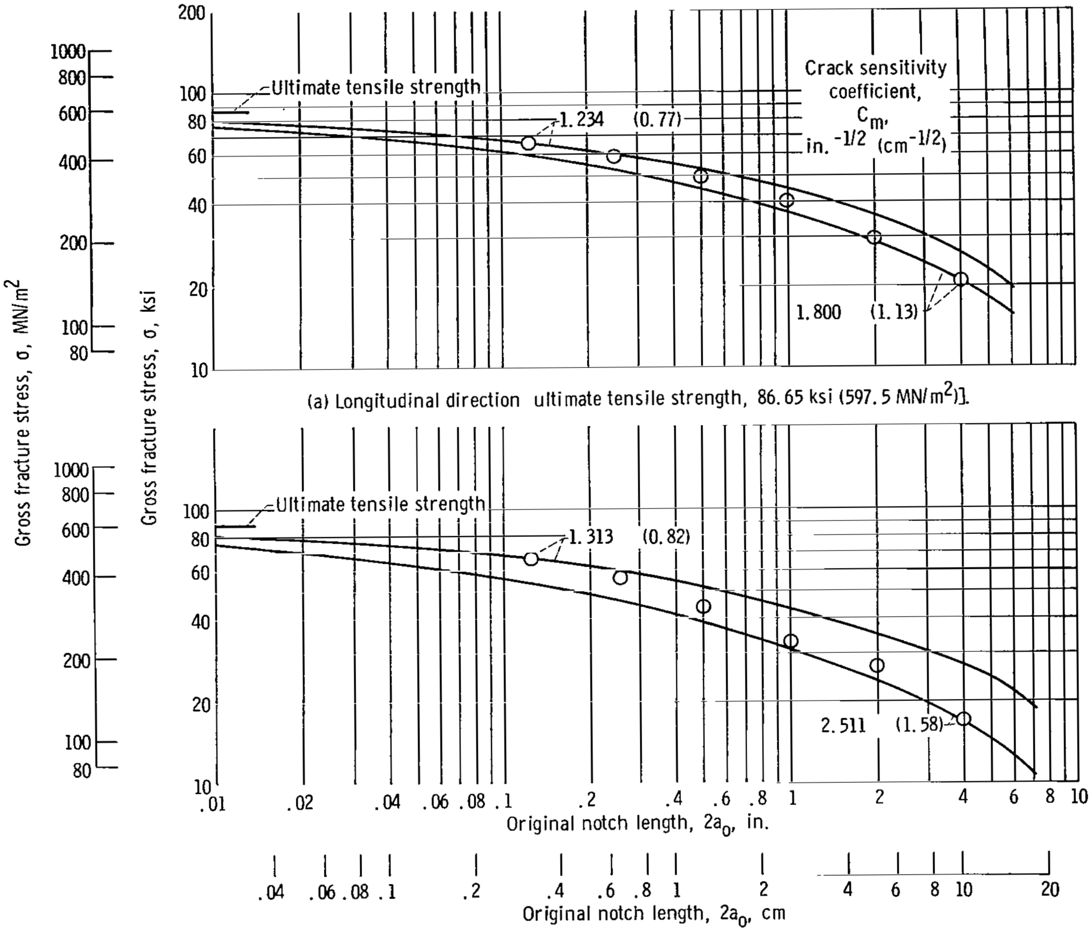
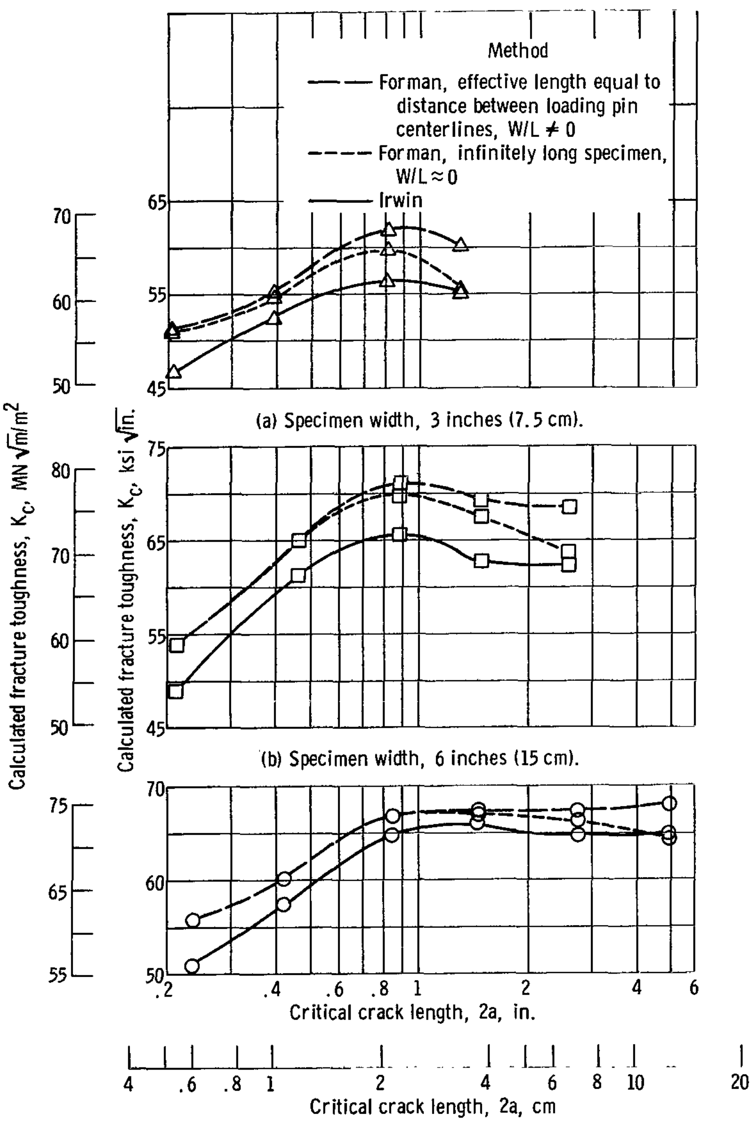


Figure 10. - Variation of crack sensitivity coefficient (ref. 5) with notch length.



(b) Transverse direction [ultimate tensile strength, 88.06 ksi (607.2 MN/m²)].

Figure 11. - Effect of crack sensitivity coefficient variation on gross fracture stress predicted by Kuhn's method (ref. 5) for 12-inch (30 cm) wide specimens at -320° F (77° K). (Curves calculated from eq. (3).)



(c) Specimen width, 12 inches (30 cm).

Figure 12. - Comparison of Forman and Irwin methods of calculating fracture toughness at -320° F (77° K). Longitudinal direction. (Curves faired point-to-point for clarity.)

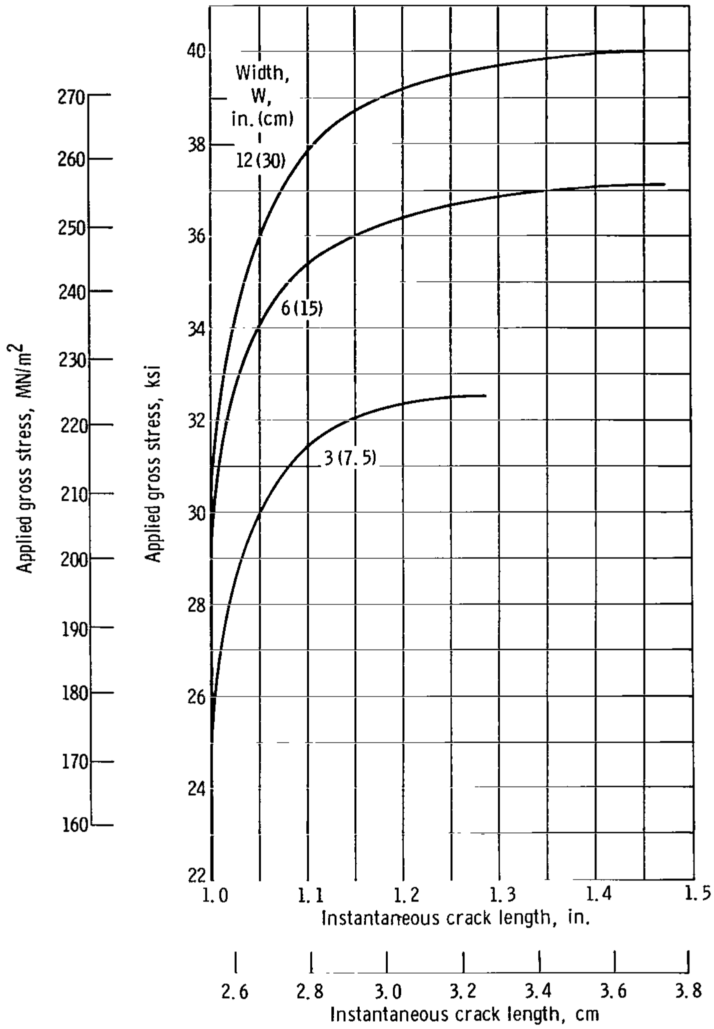


Figure 13. - Typical crack growth from 1-inch (2.5 cm) initial notch in longitudinal specimens of three widths.

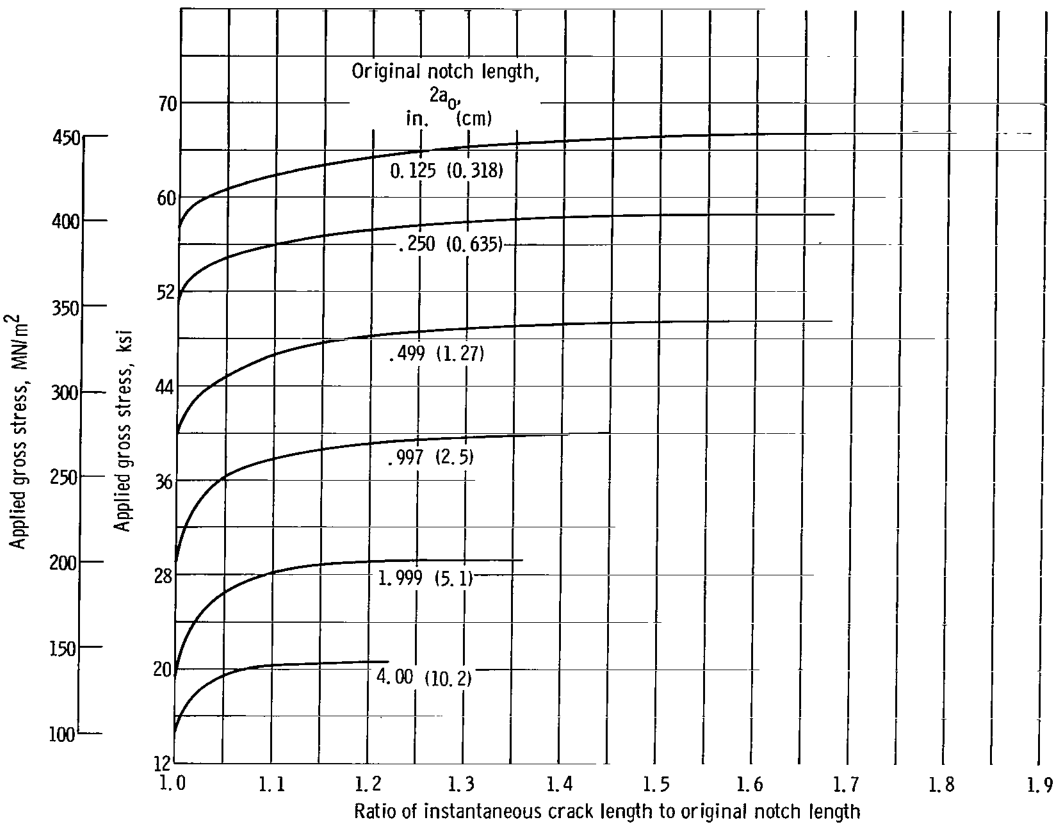


Figure 14. - Typical crack growth (normalized) from various initial notch sizes in longitudinal specimens 12 inches (30 cm) wide.

NASA-Langley, 1967 —— 17 E-3688

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